GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. _____

Project No. A-3547 GTRI/~~GIT~~ DATE 6 / 27 / 83

Project Director: W. M. Ewing ~~School~~/Lab EDL/SHD

Sponsor: Georgia-Pacific Corporation

Type Agreement: Standard Research Agreement

Award Period: From 5/9/83 To 5/30/83 (Performance) 6/30/83 (Reports)

Sponsor Amount:	This Change	Total to Date
Estimated:	$	$ 2,300
Funded:	$	$ 2,300

Cost Sharing Amount: $ _____ Cost Sharing No: _____

Title: Evaluation of a Passive Ventilation System Using the Carbon Monoxide Decay Test.

ADMINISTRATIVE DATA

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Defense Priority Rating: NA

Military Security Classification: _____

(or) Company/Industrial Proprietary: see below

RESTRICTIONS

See Attached NA Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with NA

COMMENTS:

No report, summary, advertising or publicity matter shall be released to any third party without the consent of (manufacturer) Am. Energy Products, Inc.

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FORM OCA 4

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date August 16, 1983

Project Title: Evaluation of a Passive Ventilation System Using the Carbon Monoxide Decay Test

Project No: A-3547

Project Director: W. M. Ewing

Sponsor: Georgia-Pacific Corporation

Effective Termination Date: 6/30/83

Clearance of Accounting Charges: 6/30/83

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice ~~and Closing Documents~~
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other _____

Assigned to: EDL/SHD (~~School~~/Laboratory)

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FORM OCA 10:781

A-3547

EVALUATION OF AIR EXCHANGE VARIABLES IN MANUFACTURED HOUSING

Project No. A-3547

Prepared for

Georgia-Pacific Corporation
2883 Miller Road
Decatur, Georgia 30035

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Environmental Health and Safety Division
Atlanta, Georgia 30332
Final Report
June 1983

EXECUTIVE SUMMARY

A study was conducted by William M. Ewing of the Georgia Institute of Technology to evaluate air exchange rates with respect to various parameters which were expected to increase/decrease the air exchange rate of the two homes tested. The tests indicated each home, when totally sealed, immediately after construction, has an infiltration rate of approximately 0.1 air changes per hour. The air exchange rate increased as sources of make-up air were permitted to enter each home. Air exchange rates tended to vary between the test location in the living room and the test location in the master bedroom of each home. The air exchange rate was usually higher in the living room.

At the request of the sponsor, the number of variables were increased. This necessitated increasing the number of tests to be conducted and eliminated any possibility of repeating tests. Accordingly, this project should be viewed as a pilot project with many more tests required to fully evaluate each home for each different arrangement of the variables considered.

EVALUATION OF AIR EXCHANGE VARIABLES IN MANUFACTURED HOUSING

I. INTRODUCTION

The GEORGIA TECH RESEARCH INSTITUTE conducted a study to measure air exchange rates in two newly-manufactured mobile homes. The study was conducted by Mr. William M. Ewing of Georgia Tech's Environmental Health and Safety Division. Measurements were made on May 9-11, 1983 on a single-wide and a double-wide mobile home. The purpose of the study was to evaluate changes in air exchange rates with respect to various parameters which were expected to increase/decrease the air exchange rate of the home.

The carbon monoxide decay method was used to measure rates of air exchange in each home. For this method a known concentration of carbon monoxide (CO) is generated in the enclosure for which the air exchange rate is to be determined. The decay of the carbon monoxide concentration is measured over a period of time (0.5 - 1 hours). The air exchange rate is determined by taking the natural logarithm of the final carbon monoxide contration divided by the initial concentration times the inverse of the decay period.

II. DISCUSSION OF RESULTS

Originally three mobile homes were to be tested using the carbon monoxide decay technique. However, one of the homes (unit #2) was not equipped with

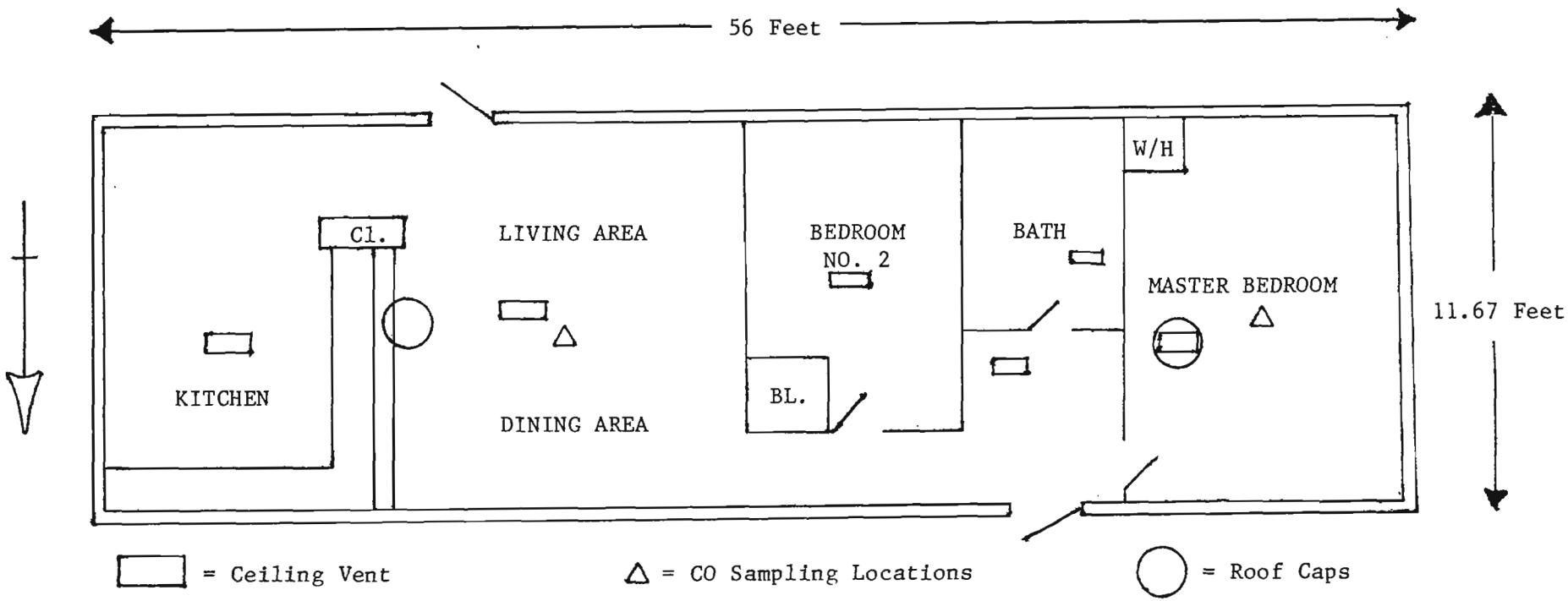
a blower and therefore could not be tested since proper mixing of the tracer gas could not be achieved. Accordingly, additional tests were performed on unit #1.

Unit #1 was a single-wide mobile home manufactured on May 5, 1983. The home's outside dimensions were measured and found to be 11.67 feet (140 inches) wide, 56 feet (672 inches) long, with 7-foot ceilings. This results in 653 square feet (ft^2) floorspace and a 4573 cubic foot (ft^3) volume. Figure I is a drawing of the home indicating the location of walls, doors, windows, ceiling vents, roof caps, and blower. Also indicated on this drawing are the two sampling locations for carbon monoxide determinations.

Unit #3 was a double-wide mobile home manufactured on May 6, 1983. The outside dimensions were 52 feet (624 inches) long and 23.5 feet (282 inches) wide. The ceiling height was 7 feet except in the living/dining area where the ceilings inclined from 7 feet at the walls to 8.5 feet at the center. The square footage calculated for this home ws 3644 ft^2 with a total volume of 8270 ft^3. Figure II is a drawing of the home depicting the locations of walls, doors, windows, ceiling vents, roof caps, and blower. A blower was installed in this unit to provide mixing of the tracer gas. Since this blower was not typical of the type used in this unit, tests to evaluate the effect of the blower on air exchange rates were not conducted.

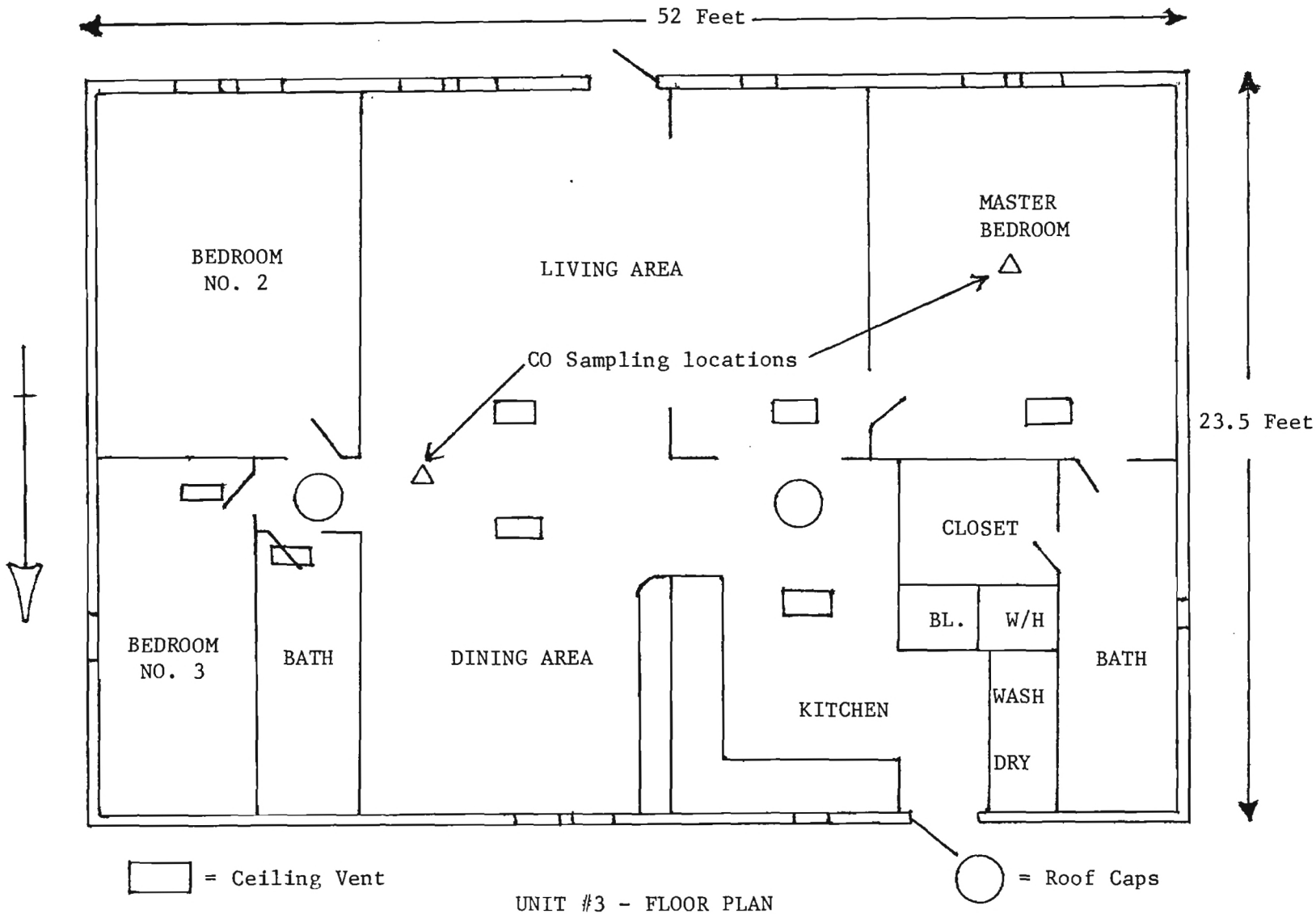
A. TEST RESULTS FOR UNIT #1

A total of 12 tests were conducted on unit #1. For these tests 4% carbon monoxide was released into the blower to provide distribution of



UNIT #1 - FLOOR PLAN
(Not To Scale)

Figure I.



UNIT #3 - FLOOR PLAN
(Not To Scale)

Figure II.

the gas throughout the home. The concentration was permitted to rise inside the home to 50-100 parts per million (ppm). Interscan carbon monoxide monitors sampled the air continuously at two locations inside the home. These locations were the center of the living room and the center of the master bedroom (see Figure I). Once the concentration of carbon monoxide had reached the desired level the carbon monoxide source was disconnected. The blower was on whenever the carbon monoxide was being injected into the home to provide proper mixing. The carbon monoxide was permitted to stabilize for approximately 15 minutes prior to beginning each test. Tests 1, 2, 2A, 3, 4, 4A and 5 were conducted on May 9, 1983. Tests 6, 7, 7A, 8, and 9 were conducted on May 10, 1983. The Interscan carbon monoxide monitors (2) were calibrated before and after each test with the data corrected as necessary.

The results of each test including actual carbon monoxide measurements and calculation of air exchange rates are included in Appendix A of this report. The results of environmental measurements conducted during each test are attached in Appendix B of this report. Figure III is a summary of the test results indicating the variables considered. For this unit the variables were the following:

Blower (on/off)

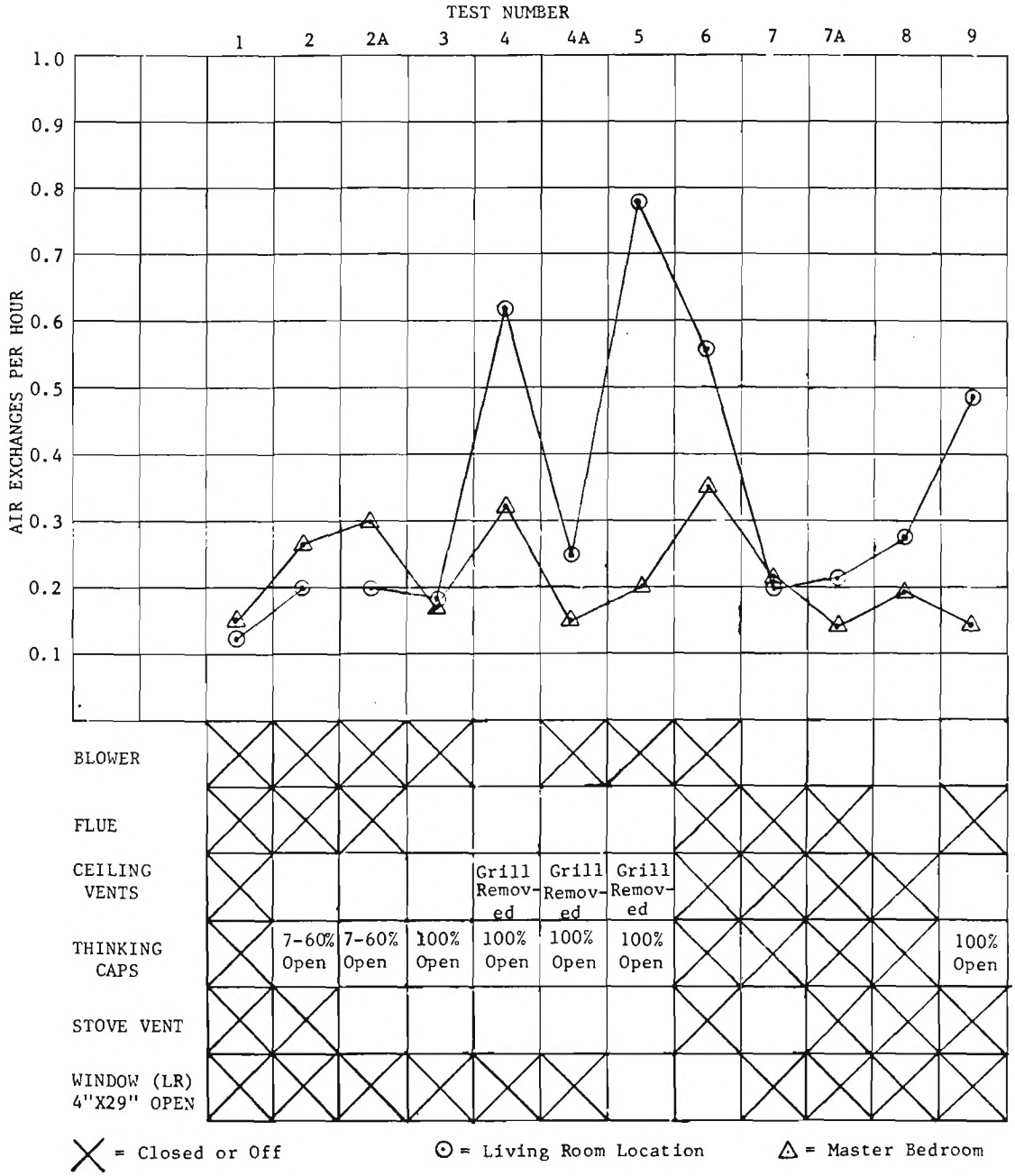
Flue (uncovered/covered)

Ceiling Vents (open/closed/removed)

Roof Caps (open/sealed)

Stove Vent (open/sealed)

Window (LR) (open 4"/closed)



SUMMARY OF TEST RESULTS
UNIT #1

Figure III.

The first test was performed (test #1) with the unit totally sealed and the blower not operating. As expected, this resulted in the lowest air exchange rate of all the tests. The calculated rates were 0.12 and 0.14 air changes per hour in the living room and master bedroom, respectively.

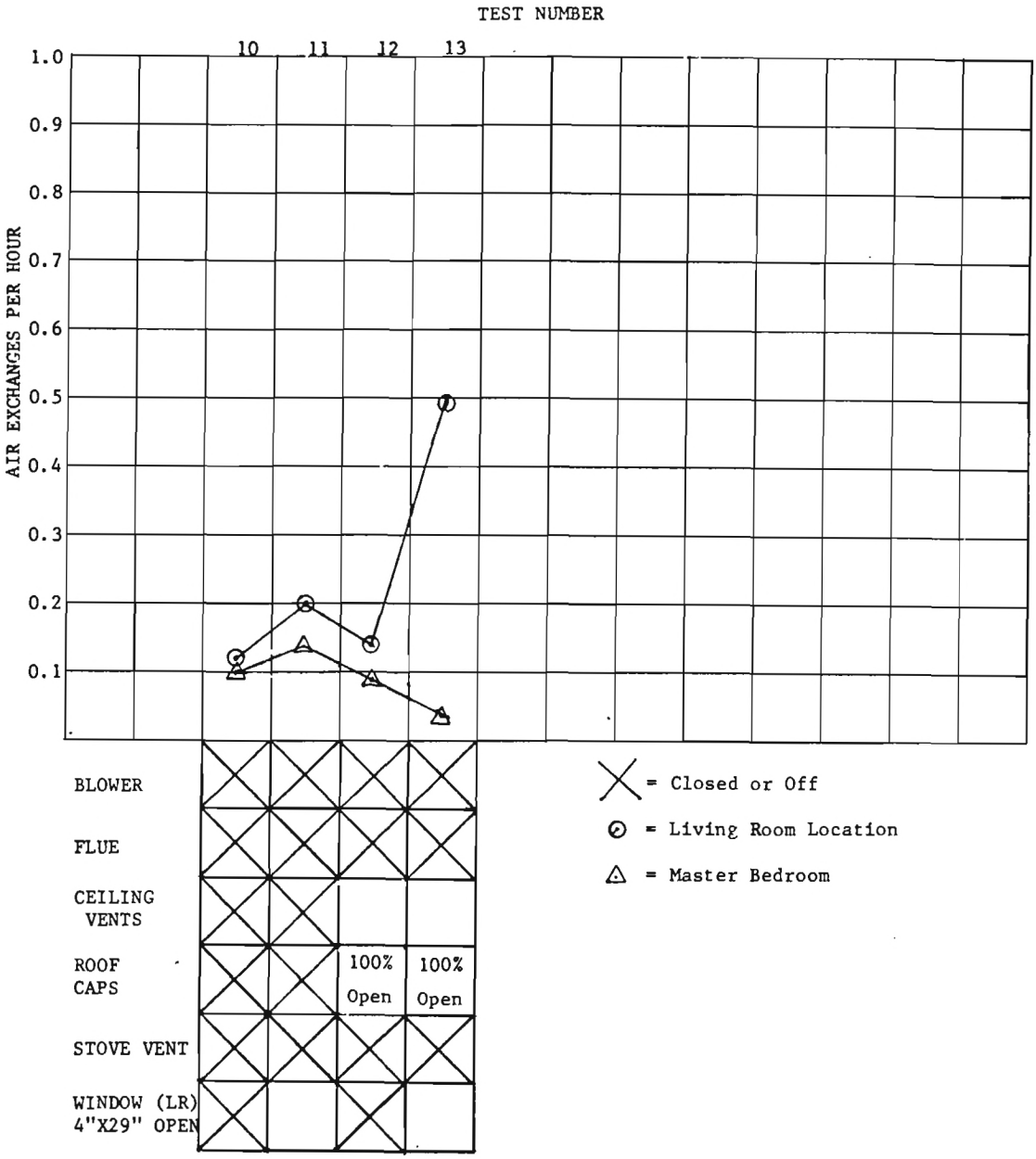
A total of 3 tests were conducted with the blower on and no major source of make-up air for dilution (tests #7, 7A, 8). The calculated air exchange rates for the two locations during these 3 tests (6 total) was in a range of 0.20 - 0.27 air changes per hour. Four tests were conducted using only the passive ventilation system with no other major source of make-up or dilution air (tests #2, 2A, 3, 4A). The results at the 8 total sampling locations were in a range of 0.15 - 0.30 air changes per hour. For all of the above seven tests there was not a significant variation in exchange rates calculated for the living room with respect to the master bedroom.

Two tests (test #4 and 9) were conducted with the blower on and the passive ventilation system operating (ceiling vents and roof caps open 100%). The arithmetic mean air exchange rate for the two locations for test numbers 4 and 9 were 0.47 and 0.31 air changes per hour. It is significant, however that the air change between the two sampling locations during each test was considerable. In each case the air exchange rate in the living room was more than double that calculated for the master bedroom. The air exchange rate for the master bedroom was 0.31 and 0.14 air changes per hour for test numbers 4 and 9, respectively. The air exchange rate for the living room for test number 4 was 0.63 and for test number 9 was 0.48 air changes per hour.

Two tests (test #5 and 6) were conducted on the home with the living room window open 4 inches (total opening of 4" x 29"). During one of these tests (#6) the remainder of the home was completely sealed. During test #5 the passive ventilation system, flue, and stove vent were open. For both tests the blower was not operating. The resulting air exchange rates indicated a mean air exchange rate of 0.49 and 0.45 air exchanges per hour for tests 5 and 6 respectively. In each test the air exchange rate was significantly higher in the living room than the master bedroom. The air exchange rate in the living room with the open window only was 0.55 air changes per hour. With the open window and the passive ventilation system operating (and flue and stove vent open) the ventilation rate in the living room increased to 0.77 air changes per hour. The air exchange rate in the master bedroom, however, for the same two tests (5 and 6) was 0.20 and 0.34 air changes per hour.

B. TEST RESULTS FOR UNIT #3

Four tests were conducted on Unit #3. The results of each test with corresponding carbon monoxide measurements and air exchange calculations are included in Appendix A of this report. Tables of environmental measurements taken during each test are included in Appendix B. Figure IV summarizes the test results indicating variables expected to affect the air exchange rate in the home. Since the blower used to mix the tracer gas was not of the type normally used in this home it did not operate during test periods. Further, since the units' ventilation system did not have a flue this was not a variable. Lastly, since testing conducted on unit #1 indicated the stove vent did not have



SUMMARY OF TEST RESULTS
UNIT #3

Figure IV.

a significant impact on the air exchange rate for the home it was kept sealed on unit #3.

The first test conducted was with the home completely sealed (test #10). The mean air exchange rate calculated was 0.11 air changes per hour with no signficant difference between the air exchange rate for the living room and the rate for the bedroom. Test #12 resulted in a mean air exchange rate of 0.11 with the home sealed except for the passive ventilation system. Again, the slightly higher air exchange rate in the living room was not significant. The two remaining tests were conducted with the living room window open (4" x 29" opening). In test #11 the remainder of the house was completely sealed. In test #13 the passive ventilation system was operating. The mean air exchange rate calculated for test #11 was 0.17 air changes per hour with no significant difference between the living room and master bedroom sampling locations. The mean air exchange rate for test #13 was 0.26 with the living room exchange rate much greater than the master bedroom.

C. ENVIRONMENTAL MEASUREMENTS

The environmental measurements taken during the air exchange tests included temperatures at two locations inside the home, ambient temperature, percent relative humidity (RH) inside and outside the home, barometric pressure in inches of mercury (inches Hg), and wind velocities (speed (mph) and direction) at locations outside the home. These data are presented in Appendix B of this report for each test. Temperature and relative humidity followed similar cycles during the three days of testing as indicated in Table I.

TABLE I

Summary of Temperature and Relative Humidity Measurements Each Day

Day	Location	Temperature Range (in °F)	Relative Humidity Range (in %)
5/9/83	Ambient	63-80	47-68
5/9/83	Unit #1	69-90	52-60
5/9/83	Unit #1 (roof cavity)	70-91	50-62
5/10/83	Ambient[1]	79-84	49-60
5/10/83	Unit #1[1]	79-91	50-57
5/11/83	Ambient[2]	77-88	37-56
5/11/83	Unit #3[2]	74-85	48-58

1 Testing conducted in afternoon only
2 Testing completed by 3 o'clock pm

Barometric pressure readings did not vary significantly during the three days of testing. The measurements were in a range of 29.90 - 30.15 inches Hg during the three-day period.

Wind speeds remained relatively constant for all tests. Although slightly higher during the frist two days of testing (unit #1) the wind was light during all test periods. The range of measurementse during the three days was 1 - 7 miles perhour. The prevailing wind direction during the first two days of testing was out of the East and out of the South during the third day of testing. Due to the location of the test homes and their proximetry to other structures and paved surfaces the wind direction actually impacting the home changed considerably since thermal currents from the paved surfaces and other structures have a great impact on air movement at ground level.

III. CONCLUSIONS

1. Complete mixing of the tracer gas was achieved only through using the blower and existing ductwork in the home. Without this, the concentration of tracer gas is not evenly distributed which will adversely affect the results.

2. The air exchange rate in the homes tested was not constant from one area of the home to the next. In these tests the exchange rate for the living room was found to be consistantly higher than the master bedroom.

3. These homes, tested at the manufacturer's facility and totally sealed, indicated an average air exchange rate of 0.10 - 0.14 air changes per hour. Under actual living conditions (occupied), following transportation to a permanent site, the air exchange rate would be different.

4. The presence of the operating blower alone without any major source of make-up air only provided a slight increase in the air exchange rate for the home. This slight increase (0.1 air exchanges per hour or less) was probably due to small air leaks in the structure of the home and in the ductwork.

5. Over the base test situation (fully sealed), the air exchange rate showed a slight increase (0.1 air exchanges per hour or less) when only vents were open and there was no other major source of make-up air.

6. When the blower and passive ventilation system were both operating the air exchange rate increased significantly at the living room sampling location of unit #1. The increase with both operating for the living room was of the order of 0.4 - 0.5 air changes per hour. A slight increase in the air exchange rate occurred in the master bedroom. It is possible that the increased air exchange rate in the living room area is due to channeling of dilution air from the east roof cap to the blower inlet located off the west end of the living room.

7. An open window alone provides a significant increase in the air exchange rate for the living room of unit #1 (open window on north side of living room). A more moderate increase was noted in the master bedroom of unit #1. Based on these data, an open window alone will provide a significant increase in the air exchange rate for that room.

8. When a window is opened in the same area where the passive system is operating it appears the air exchange rate is further increased since make-up air can enter through one source and exit through another. This was evident in two tests (#5 and #13). Also, in each test their was a significant decline in the air exchange rate in the bedrooms. This supports the idea that the air is again channeling from one opening to the next nearest opening; by-passing the master bedroom all together.

9. The variables affecting the air exchange rate (blower, window, etc.) appear to be additive in nature for the living room locations in both units tested. Clearly, substantially more testing would be required to establish the values for each variable.

10. A ventilation system must have two components, an air inlet and an exhaust. The effectiveness of a passive exhaust device is directly dependent on the rate of fresh air induced into the home.

11. The presence of a stove vent did not appear to significantly affect the air exchange rates.

12. The air exchange rate in the double-wide home tested was generally less than that found in a single-wide home under similar conditions.

13. Since the meteorological data indicated little day-to-day variation, little can be concluded regarding the effects of temperature changes, humidity changes, calm vs. windy days, etc.

IV. RECOMMENDATIONS

1. Carbon monoxide should not be used as a tracer gas when conducting air exchange measurements in occupied structures. Alternatively, a less toxic gas such as sulfur hexafluoride should be used.

2. Since much of each occupant's time is spent in the bedroom(s), air exchange studies in mobile homes should include a bedroom as one of the sampling locations.

3. Additional work is necessary to determine if the air exchange rate of a mobile home is affectd by (1) transportation, (2) installation at final site,

and (3) occupancy. The two units tested should therefore be evaluated again once they have been transported to their final destination.

4. A study should be designed and conducted to determine the effect of the blower alone on air exchange rates. Testing could be conducted on a home equipped with a variable-speed blower. In this manner, it can be determined if the air exchange rate increases with the blower speed.

5. Methods of providing induced fresh air for tightly sealed homes should be investigated.

6. A model should be developed which will relate the many variables to the actual air exchange rate of the home. The model might be developed from existing one, two or multi-compartment models currently in use for buildings. The model developed should be specific for the mobile home industry. It would also serve as a valuable tool in determining steady-state concentrations of indoor pollutants such as formaldehyde.

7. This project can only be viewed as a pilot project. To thoroughly evaluate the effects of the many variables on the air exchange rate of the home would require hundreds of tests, clearly beyond the scope of this project. Further research which would permit replicate and long duration testing is urgently needed in this area.

This report prepared by:

William M. Ewing
Industrial Hygienist

This report approved by:

James L. Burson, CIH, CSP
Chief, Environmental Health and
Safety Division

WME:JLB:sek

APPENDIX A

AIR EXCHANGE TEST RESULTS

Test No. 1
May 9, 1983

CONDITIONS: Home totally sealed, including ceiling vents, thinking caps, furnace flue, stove vent. Windows and doors closed.

TIME	Carbon Monoxide (ppm) (A)	(B)
1000	81	82
1005	82	81
1010	81	80
1015	81	79
1020	80	79
1025	79	78
1030	78	78
1035	76	78
1040	75	77
1045	74	75
1050	74	73
1055	73	72
1100	72	71

AIR EXCHANGE RATE (I) = $-\ln \frac{C_f}{C_i} \frac{1}{\Delta t}$

$I_A = -\ln \frac{72}{81} \frac{1}{1.0}$

I_A= 0.12 Air changes per hour

$I_B = -\ln \frac{71}{82} \frac{1}{1.0}$

I_B= 0.14 air changes per hour

$I_{Avg.}$= 0.13 Air changes per hour

I_A - Air exchange rate from the center of living room (58" height), east end of home.

I_B - Air exchange rate from the master bedroom (63" height), west end of home.

Test No. 2
May 9, 1983

CONDITIONS: Home sealed as in test No. 1 except ceiling vents open and thinking caps uncovered (in winter position (7-10% bleed) at start of test #2, open 60% at end of test #2A. Flue covered.

TIME	Carbon Monoxide (ppm) (A)	(B)
1145	65	67
1150	64	65
1155	63	63
1200	61	62
1205	60	62
1210	60	61
1215	59	59
1220	59	58
1225	57	57
1230	56	56
1235	55	54
1240	54	54
1245	53	52

$I_A = -\ln \frac{53}{65} \cdot \frac{1}{1.0}$

I_A= 0.20 Air changes per hour

$I_B = -\ln \frac{53}{67} \cdot \frac{1}{1.0}$

I_B= 0.25 Air changes per hour

I_{Avg}= 0.225 Air changes per hour

I_A - Air exchange rate from the center of living room (58" height), east end of home.

I_B - Air exchange rate from the center of the master bed room (63" height), west end of home.

Test No. 2A
May 9, 1983

CONDITIONS: Same as test #2 except stove vent was unsealed (motor off). Note that at the conclusion of this test the think-caps were found to be about 60% open.

TIME	Carbon Monoxide (ppm) (A)	(B)
1255	52	51
1300	51	50
1305	50	48
1310	49	46
1315	48	45
1320	48	45
1325	47	44

$$I_A = -\ln \frac{47}{52} \quad \frac{1}{0.5}$$

I_A = 0.20 Air changes per hour

$$I_B = -\ln \frac{44}{51} \quad \frac{1}{0.5}$$

I_B = 0.30 Air changes per hour

$$I_{Avg} = 0.25 \text{ Air changes per hour}$$

I_A - Air exchange rate from center of the living room (58" height), east end of h-me.

I_B - Air exchange rate from center of the master bedroom (63" height), west end of home.

Test No. 3
May 9, 1983

CONDITIONS: Home sealed, ceiling vents open, thinking caps open 100% at summertime setting, stove vent open, blower off. Flue open.

TIME	Carbon Monoxide (ppm) (A)	(B)
1430	82	81
1435	80	79
1440	79	77
1445	75	78
1450	76	76
1455	75	75
1500	73	75
1505	72	74
1510	70	73
1515	69	72
1520	70	71
1525	69	70
1530	68	69

$$I_A = -\ln \frac{68}{82} \frac{1}{1.0}$$

$$I_B = -\ln \frac{69}{81} \frac{1}{1.0}$$

I_A = 0.18 Air changes per hour

I_B = 0.17 Air changes per hour

$$I_{Avg} = 0.175 \text{ Air changes per hour}$$

I_A - Air exchange rate from the center of the living room (58" height), east end of home

I_B - Air exchange rate from center of the master bedroom (63" height), west end of home.

Test No. 4
May 9, 1983

CONDITIONS: Ceiling vents removed, thinking caps open 100%, flue open, Blower ON, remainder of house sealed except stove vent.

TIME	Carbon Monoxide (ppm) (A)	(B)
1620	79	74
1625	77	73
1630	72	72
1635	67	69
1640	63	69
1645	59	66
1650	58	64
1655	54	62
1700	52	60

$$I_A = -\ln \frac{52}{79} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{60}{74} \quad \frac{1}{0.67}$$

I_A = 0.63 Air changes per hour

I_B = 0.31 Air changes per hour

$$I_{Avg} = 0.47 \text{ Air changes per hour}$$

I_A - Air exchange rate from the center of living room (58" height), east end of home

I_B - Air exchange rate from the center of master bedroom (63" height), west end of home.

Test No. 4A
May 9, 1983

CONDITIONS: Same conditions as the test #4 except the blower was turned OFF.

TIME	Carbon Monoxide (ppm) (A)	(B)
1710	52	54
1715	51	53
1720	50	53
1725	49	53
1730,	48	52
1735	47	52
1740	46	51
1745	45	50
1750	44	49

$$I_A = -\ln \frac{44}{52} \quad \frac{1}{0.67}$$

I_A = 0.25 Air changes per hour

$$I_B = -\ln \frac{49}{54} \quad \frac{1}{0.67}$$

I_B = 0.15 Air changes per hour

$$I_{Avg} = 0.20 \text{ Air changes per hour}$$

I_A - Air exchange rate from the center of living room (58" height), east end of home.

I_B - Air exchange rate from center of master bedroom (63" height), west end of home.

Test No. 5
May 9, 1983

CONDITIONS: Ceiling vents removed, thinking caps open 100%, flue open BlowerOFF, remainder of house sealed except stove vent and one window (open 4", 29" long). Same as test #4A except window is open.

TIME	Carbon Monoxide (ppm) (A)	(B)
1802	47	42
1807	42	41
1812	40	39
1817	38	40
1822	35	40
1827	34	39
1832	32	38

$$I_A = -\ln \frac{32}{47} \frac{1}{0.5}$$

I_A= 0.77 Air changes per hour

$$I_B = -\ln \frac{38}{42} \frac{1}{0.5}$$

I_B= 0.20 Air changes per hour

$$I_{Avg} = 0.485 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of living room (58" height), east end of home.

I_B - Air exchange rate for the master bedroom (63" height), west end of home.

Test No. 6
May 10, 1983

CONDITIONS: Home completely sealed except for the living room window open 4" (29" length). Thinking caps, flue, ceiling vents, all sealed. Blower OFF.

TIME	Carbon Monoxide (ppm) (A)	(B)
1250	62	64
1255	60	63
1300	58	61
1305	55	59
1310	53	57
1315	52	56
1320	49	54
1325	47	54

$$I_A = -\ln \frac{47}{62} \quad \frac{1}{0.5}$$

I_A = 0.55 Air changes per hour

$$I_B = -\ln \frac{54}{64} \quad \frac{1}{0.5}$$

I_B = 0.34 Air changes per hour

$$I_{Avg} = 0.445 \text{ Air changes per hour}$$

I_A = Air exchange rate for the center of living room (58" height), east end of home

I_B = Air exchange rate for the center of the master bedroom (63" height), west end of home.

Test No. 7
May 10, 1983

CONDITIONS: Entire unit sealed, including ceiling vents, thinking caps, flue, windows, and doors. Blower ON. Stove vent open, not on.

TIME	Carbon Monoxide (ppm) (A)	(B)
1400	56	58
1405	55	57
1410	54	56
1415	53	55
1420	53	54
1425	52	52
1430	50	51
1435	49	51
1440	49	50

$$I_A = -\ln \frac{49}{56} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{50}{58} \quad \frac{1}{0.67}$$

I_A = 0.20 Air changes per hour

I_B = 0.22 Air changes per hour

$$I_{Avg} = 0.21 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of living room (58" height), east end of home

I_B - Air exchange rate for the center of the master bedroom (63" height), west end of home.

Test No. 7A
May 10, 1983

CONDITIONS: Home completely sealed including stove vent. Blower ON. Same as test #7 except stove vent covered.

TIME	Carbon Monoxide (ppm) (A)	(B)
1505	45	46
1510	44	45
1515	43	45
1520	41	45
1525	42	45
1530	41	45
1535	40	44
1540	40	43
1545	39	42

$$I_A = -\ln \frac{39}{45} \quad \frac{1}{0.67}$$

I_A = 0.21 Air changes per hour

$$I_B = -\ln \frac{42}{46} \quad \frac{1}{0.67}$$

I_B = 0.14 Air changes per hour

I_{Avg} = 0.175 Air changes per hour

I_A - Air exchange rate for the center of living room (height = 58"), east end of home.

I_B - Air exchange rate for the master bedroom (height = 63"), west end of home.

Test No. 8
May 10, 1983

CONDITIONS: Home sealed, including thinking caps, stove vent, ceiling vents, windows, doors, flue OPEN, blower ON.

TIME	Carbon Monoxide (ppm) (A)	(B)
1630	60	58
1635	58	57
1640	57	55
1645	56	55
1650	55	54
1655	52	53
1700	51	53
1705	50	52
1710	50	51

$$I_A = -\ln \frac{50}{60} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{51}{58} \quad \frac{1}{0.67}$$

I_A = 0.27 Air changes per hour

I_B = 0.19 Air changes per hour

$$I_{Avg} = 0.23 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of the living room (58" height), east end of home.

I_B - Air exchange rate for the master bedroom (63" height), west end of home.

Test No. 9
May 10, 1983

CONDITIONS: Home sealed, including flue, stove vent, windows, doors. ceiling vents open, thinking caps open 100%, blower ON.

TIME	Carbon Monoxide (ppm) (A)	(B)
1735	44	44
1740	43	43
1745	41	43
1750	40	42
1755	38	42
1800	37	41
1805	35	41
1810	34	41
1815	32	40

$$I_A = -\ln \frac{32}{44} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{40}{44} \quad \frac{1}{0.67}$$

I_A = 0.48 Air changes per hour

I_B = 0.14 Air changes per hour

$$I_{Avg} = 0.31 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of living room (height 58"), east end of home.

I_B - Air exchange rate for the center of the master bedroom (height 63"). west end of home.

Test No. 10
May 11, 1983

CONDITIONS: Home completely sealed, ceiling vents closed, thinking caps sealed, windows, doors closed. Stove vent sealed. Blower off. No flue on this home.

TIME	Carbon Monoxide (ppm) (A)	(B)
1050	57	54
1055	56	53
1100	56	53
1105	55	52
1110	55	52
1115	54	52
1120	54	51
1125	53	51
1130	52	50
1135	52	50

$$I_A = -\ln \frac{52}{57} \quad \frac{1}{0.75}$$

$$I_B = -\ln \frac{50}{54} \quad \frac{1}{0.75}$$

I_A = 0.12 Air changes per hour

I_B = 0.10 Air changes per hour

$$I_{Avg} = 0.11 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of the living room, center of home.

I_B - Air exchange rate for the master bedroom (center), west end of home.

Test No. 11
May 11, 1983

CONDITIONS: Home completely sealed including ceiling vents, thinking caps, stove vent, doors, and windows, EXCEPT north LR window open 4" (29" length)

TIME	Carbon Monoxide (ppm) (A)	(B)
1200	73	62
1205	72	60
1210	71	60
1215	70	59
1220	68	59
1225	67	58
1230	66	58
1235	65	57
1240	64	57

$$I_A = -\ln \frac{64}{73} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{57}{62} \quad \frac{1}{0.67}$$

I_A= 0.20 Air changes per hour

I_B= 0.13 Air changes per hour

$$I_{Avg} = 0.165 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of the living room, center of home

I_B - Air exchange rate for the master bedroom (center), west end of home.

Test NO. 12
May 11, 1983

CONDITIONS: Home sealed except for the ceiling vents and the thinking caps (open 100%). Windows, doors sealed, blower off.

TIME	Carbon Monoxide (ppm) (A)	(B)
1300	58	55
1305	57	54
1310	57	54
1315	55	53
1320	54	53
1325	54	52
1330	53	52
1335	53	52
1340	53	52

$$I_A = -\ln \frac{53}{58} \quad \frac{1}{0.67}$$

$$I_B = -\ln \frac{52}{55} \quad \frac{1}{0.67}$$

I_A = 0.13 Air changes per hour

I_B = 0.08 Air changes per hour

$$I_{Avg} = 0.105 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of living room, near center of home.

I_B - Air exchange rate for the center of the master bedroom, west end of home.

Test No. 13
May 11, 1983

CONDITIONS: Home sealed except north window open 4" (29" length). Ceiling vents open, thinking caps open 100%. Blower OFF.

TIME	Carbon Monoxide (ppm) (A)	(B)
1410	43	45
1415	41	45
1420	40	45
1425	36	45
1430	35	44
1435	34	44
1440	35	44
1445	33	44
1450	31	44

$$I_A = -\ln \frac{31}{43} \quad \frac{1}{0.67}$$

I_A= 0.49 Air changes per hour

$$I_B = -\ln \frac{44}{45} \quad \frac{1}{0.67}$$

I_B= 0.03 Air changes per hour

$$I_{Avg} = 0.26 \text{ Air changes per hour}$$

I_A - Air exchange rate for the center of the living room, near center of home.

I_B - Air exchange rate for the center of the master bedroom, west end of home.

APPENDIX B

ENVIRONMENTAL MONITORING RESULTS

TEMPERATURE, HUMIDITY, PRESSURE AND WIND SPEED DATA - TEST NO. 1

TIME	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
0915	63	59	78	Ambient
0923	69	60	60	Kitchen (east end of home)
0926	70	61	60	Kitchen (roof cavity)
0928	69	60	60	Bedroom (west end of home)
0930	70	61	53	Bedroom (roof cavity)
0947	68	62	68	Ambient
1031	70	62	64	Ambient
1102	70	63	65	Ambient
1104	72	62	55	Kitchen (east end of home)
1106	72	62	58	Bedroom (west end of home)
1108	74	64	55	Kitchen (roof cavity)
1110	75	65	60	Bedroom (roof cavity)

Barometric Pressure Readings

TIME	Inches Hg
0947	29.94
1031	29.95
1102	29.95

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
0952	NE	2-7
1033	ENE	1-5
1136	ENE	1-7

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NOS. 2 & 2A

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1104	72	62	55	Kitchen (east end of home)
1106	72	62	58	Bedroom (west end of home)
1108	74	64	58	Kitchen (roof cavity)
1110	75	65	60	Bedroom (roof cavity)
1135	70	63	68	Ambient
1215	77	66	57	Ambient
1245	76	66	59	Ambient
1328	76	66	57	Bedroom (west end of home)
1330	81	71	62	Bedroom (roof cavity)
1334	79	68	59	Kitchen (east end of home)
1335	81	70	58	Kitchen (roof cavity)
1338	79	68	58	Ambient

Barometric Pressure Readings

Time	Inches Hg
1135	29.95
1215	29.95
1245	29.95
1338	29.95

Wind Speed And Direction Measurements

Time	Direction (from)	Speed (MPH)
1136	ENE	1-7
1218	N	1-4
1247	ENE	1-3
1343	ENE	1-4

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 3

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1328	76	66	57	Bedroom (west end of home)
1330	81	71	61	Bedroom (roof cavity)
1334	79	68	59	Kitchen (east end of home)
1335	81	70	58	Kitchen (roof cavity)
1338	80	68	57	Ambient
1432	80	67	53	Ambient
1503	81	67	50	Ambient
1532	80	66	47	Ambient
1541	84	70	52	Bedroom (west end of home)
1543	87	73	50	Bedroom (roof cavity)
1548	85	73	57	Kitchen (east end of home)
1550	88	74	53	Kitchen (foof cavity)

Barometric Pressure Readings

Time	Inches Hg
1338	29.95
1432	29.93
1503	29.93
1532	29.93

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1343	ENE	1-4
1503	ESE	2-5
1628	ENE	1-3

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NOS. 4 & 4A

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1541	84	70	52	Bedroom (west end of home)
1543	87	73	50	Bedroom (roof cavity)
1548	85	73	57	Kitchen (east end of home)
1550	88	74	52	Kitchen (roof cavity)
1619	80	67	52	Ambient
1652	80	67	52	Ambient
1746	78	67	57	Ambient
1751	88	75	56	Kitchen (east end of home)
1753	89	76	55	Kitchen (roof cavity)
1754	90	76	53	Bedroom (west end of home)
1755	91	79	58	Bedroom (roof cavity)

Barometric Pressure Readings

Time	Inches Hg
1619	29.91
1952	29.91
1746	29.90

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1628	ENE	1-3
1651	ENE	1-3
1747	NNE	1-3

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - YEST NO. 5

Time	Dry Bulb (^{o}F)	Wet Bulb (^{o}F)	Relative Humidity (%)	Location
1746	78	67	57	Ambient
1751	88	75	56	Kitchen (east end of home)
1753	89	76	55	Kitchen (roof cavity)
1754	90	76	54	Bedroom (west end)
1755	91	79	59	Bedroom (roof cavity)
1831	78	65	50	Ambient
1832	86	73	55	Kitchen (east end of home)
1834	85	73	57	Kitchen (roof cavity)
1835	88	74	53	Bedroom (west end of home)
1837	88	75	56	Bedroom (roof cavity)

Barometric Pressure

Time	inches Hg
1746	29.90
1832	29.90

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1747	NNE	1-3

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 6

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1220	79	67	57	Bedroom (west end of home)
1222	79	67	54	Kitchen (east end of home)
1236	79	68	60	Ambient
1330	84	70	50	Ambient
1335	82	68	50	Kitchen (east end of home)
1337	81	69	52	Bedroom (west end of home)

Barometric Pressure Readings

Time	inches Hg
1236	30.10
1330	30.10

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1246	ENE	1-5
1326	N	1-5

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NOS. 7 & 7A

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1330	84	70	50	Ambient
1335	82	68	50	Kitchen (east end of home)
1337	81	69	54	Bedroom (west end of home)
1542	85	72	53	Kitchen (east end of home)
1543	86	73	57	Bedroom (west end of home)
1552	83	69	49	Ambient

Barometric Pressure Readings

Time	Inches Hg
1330	30.10
1552	30.06

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1326	E	1-5
1558	ENE	1-6

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 8

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1542	85	72	53	Kitchen (east end of home)
1543	86	73	57	Bedroom (west end of home)
1552	83	69	49	Ambient
1713	88	74	53	Kitchen (east end of home)
1715	89	76	53	Bedroom (west end of home)
1718	84	70	50	Ambient

Barometric Pressure Readings

Time	Inches Hg
1552	30.06
1718	30.05

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1558	ENE	1-6
1722	ENE	1-5

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 9

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1713	88	74	53	Kitchen (east end of home)
1715	89	76	56	Bedroom (west end of home)
1718	84	70	50	Ambient
1818	89	76	56	Kitchen (east end of home)
1820	91	78	56	Bedroom (west end of home)
1824	82	68	49	Ambient

Barometric Pressure Readings

Time	Inches Hg
1718	30.05
1825	30.04

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1722	ENE	1-5
1830	E	1-5

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 10

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
0935	75	64	55	East end #2 bedroom
0936	74	64	58	Central living room
0938	74	64	58	West end master bedroom
0941	77	66	56	Ambient
1115	82	67	46	Ambient
1138	82	68	48	Ambient
1140	79	67	52	East end #2 bedroom
1142	78	67	57	Central living room
1144	78	66	55	West end master bedroom

Barometric Pressure Readings

Time	Inches Hg
0941	30.15
1115	30.14
1138	30.14

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
0950	W	1-3
1133	S	1-3

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 11

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1138	82	68	48	Ambient
1140	79	67	52	East end #2 bedroom
1142	77	67	57	Central living room
1144	77	66	55	West end master bedroom
1213	85	69	45	Ambient
1242	80	67	51	East end #2 Bedroom
1244	80	66	48	Central living room
1246	79	67	53	West end master bedroom
1250	85	66	39	Ambient

Barometric Pressure Readings

Time	Inches Hg
1138	30.14
1213	30.13

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1133	S	1-3
1236	SE	1-5

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 12

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1242	80	67	51	East end #2 bedroom
1244	80	66	48	Central living room
1246	79	67	53	West end master bedroom
1250	85	66	39	Ambient
1349	88	70	40	Ambient
1352	84	71	55	Central living room
1354	85	70	50	East end #2 bedroom
1355	83	71	54	West end master bedroom

Barometric Pressure Readings

Time	Inches Hg
1250	30.09
1349	30.08

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1236	S	1-3
1337	ESE	1-3

TEMPERATURE, HUMIDITY, PRESSURE, AND WIND SPEED DATA - TEST NO. 13

Time	Dry Bulb (°F)	Wet Bulb (°F)	Relative Humidity (%)	Location
1349	88	70	40	Ambient
1352	84	71	55	Central living room
1354	85	70	50	East end #2 bedroom
1355	83	71	54	West end master bedroom
1446	88	68	37	Ambient
1455	85	71	52	East end #2 bedroom
1457	85	70	48	Central living room
1458	85	71	52	West end bedroom

Barometric Pressure Readings

Time	Inches Hg
1349	30.08
1446	30.07

Wind Speed and Direction Measurements

Time	Direction (from)	Speed (MPH)
1337	SE	1-4
1446	SE	1-6

APPENDIX C

PROCEDURE FOR THE DETERMINATION OF AIR EXCHANGE RATES USING CARBON MONOXIDE

PROCEDURE FOR THE DETERMINATION OF AIR EXCHANGE RATE USING CARBON MONOXIDE

Principle of the Method: A known concentration of carbon monoxide (CO) is generated in the enclosure for which the air exchange rate (I) is to be determined. The concentration of carbon monoxide is then measured over time (t). The resultant value gives the air exchange rate in cubic feet per hour (CFH).

Apparatus:

1) Source of 4% (40,000 ppm) carbon monoxide. CAUTION - CO at this concentration is lethal.

2) Two-stage regulator equipped with a 1/4-inch nipple.

3) 50 feet of3/8" tygon tubing.

4) 2 carbon monoxide detectors, Interscan CO meter or equivalent.

5) 2 strip chart recorders.

6) Adjustable wrench.

Procedure:

1) Connect the two-stage regulator to the cylinder of 4% CO using the adjustable wrench. Be sure the regulator is turned off. Connect the nipple and a suitable length of tygon tubing to the regulator outlet.

2) Place one calibrated CO meter outside the enclosure and attach a strip chart to record the ambient level during the entire test. Record the time, chart speed, attenuation, range, and initial concentration.

3) Attach a suitable length of tygon tubing to a second calibrated CO meter which will collect air from within the enclosure. Attach a strip chart and record data as in procedure 2.

4) Introduce 4% CO to the structure until the CO meter monitoring inside the structure reads approximately 75 ppm*. Turn off CO gas. Mark time on strip chart. Continue reading CO concentration inside and outside structure for .5hours.

Calculations: The air exchange rate is calculated using the following formula.

$$I = -\ln \left[\frac{C_f}{C_i} \right] \frac{1}{\Delta t}$$

where: I = air exhange rate in CFH
C_i = initial CO concentration in ppm
C_f = final CO concentration in ppm
Δt = duration of test in hours

*For a 6600 ft^3 enclosure approximately 200 psi, 4% CO will be needed to attain 75 ppm.

For further information: See ASTM Special Technical Publication No. 719, Building Air Change Rate and Infiltration Measurement by Hunt, King, and Trechsel.

NOTE: The results may be presented graphically by plotting the gas concentration (y axis) versus time (x axis) on semilog paper (2 or 3 cycle).